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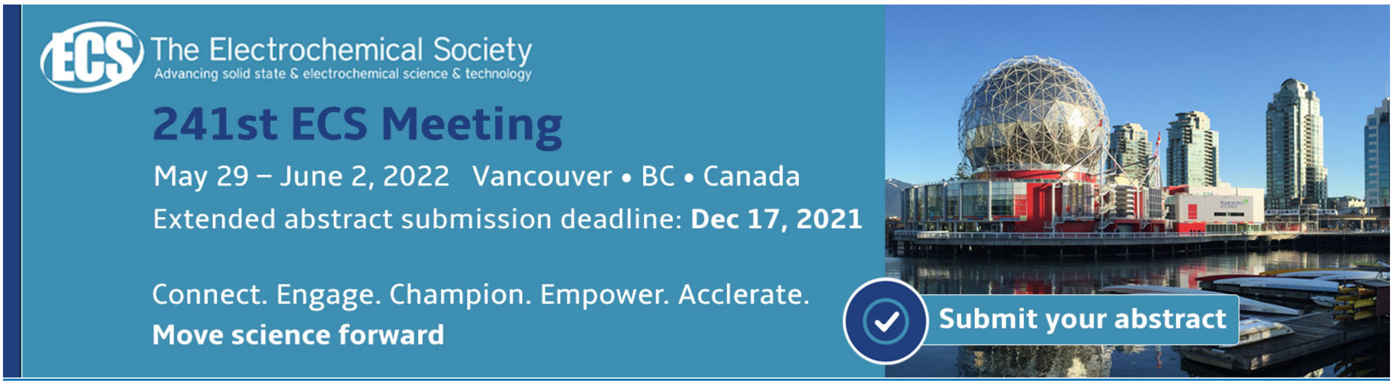

Thermal performance of a novel lightweight emergency construction system in different climates

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Abstract. Prefabricated, lightweight construction systems, thanks to their quicker construction processes, cheapness, higher portability, and adaptability, are increasingly proposed all around the world as emergency architectures (after natural disasters, pandemics, etc.), and as affordable housing solutions in countries with increasing housing demand. Due to their low thermal inertia, however, these buildings are often characterized by poor thermal performance in hot climates due to indoor overheating. The possible application of passive cooling measures is often investigated to improve their thermal performance. Among others, cool materials present some advantages in terms of ease of application and costs. However, few studies investigated the impact of this passive strategy on the thermal performance of emergency buildings. For this reason, this work evaluates the impact of cooling materials on the thermal performance of a novel lightweight prefabricated construction system (HOMEDONE) based on the assembly of reinforced-EPS panels. First, a numerical model of an experimental mock-up was created and calibrated on experimental data. Then, the thermal performance of a typical temporary housing solution was numerically evaluated under different climatic locations. Finally, the effectiveness of cooling finishing materials is investigated. The potential of cooling materials in reducing the energy demand for the studied construction system is then highlighted.

1. Introduction

In the last decades, due to the interplay between climate, natural disasters, conflict, hunger, poverty, and persecution, the number of internally displaced persons (IDPs), i.e. people displaced within their own country, is dramatically increased [1,2]. According to UNHCR, from 2010 at least 100 million people have been forced to leave their homes, seeking refuge within or outside the borders of their country. Among them, only 31% were able to return to their places of residence or to find other long-lasting solutions while the others joined the number of displaced from previous decades. As a result, by the end of 2019, the number of forcibly displaced people all around the world has grown to 79.5 million, nearly doubling the 2010 number (41 million) and increasing that of 2018 (70.8 million) [1,2].

As the number of internally displaced persons (IDPs) increases, there is also a strong need to increase their living conditions. Many IDPs, indeed, live in overcrowded, sub-standard conditions, favoring the creation and growth of slums in the poorest peripheral urban contexts [3]. To limit this scenario, when humanitarian crises occur, one of the primary objectives of governments and international organizations is to promptly help IDPs to find durable and adequate housing solutions to allow them to rebuild their lives and to ensure a resilient urban development [1,2]. However, since providing new housing may take time, temporary housing solutions are one of the primary resources in these situations.

Lightweight prefabricated construction systems are often proposed as temporary architectures to quickly respond to humanitarian emergencies, mainly thanks to their capacity to ensure high speed and ease of construction, portability, affordability, and adaptability, which are fundamental characteristics in an emergency scenario [4]. The importance of these systems has been also recently emphasized during the recent COVID-19 pandemic, when, to cope with the health emergency, the national authorities were forced to build entire field hospitals in a few weeks, or to expand existing ones, to add thousands of beds for health treatment or quarantine [5].

However, being mainly designed to ensure a high construction speed and short periods of occupation (generally two to three years in the case of temporary housing), such systems are often characterized by low durability, comfort, and energy performance if compared to common housing solutions. For instance, in the absence of an adequate environmental control system, as can often happen in a post-disaster scenario due to lack of energy supply, or due to economic restrictions in developing countries, severe internal thermal discomfort can occur due to the indoor summer overheating, especially in warm and temperate climates [6]. As a result, the occupants may be subjected to further physical and psychical distress by these conditions, even causing health issues in case of prolonged periods of occupation [7–9]. Nonetheless, it is not uncommon for displaced people to remain in these buildings for a long time, even decades [1,2,10].

The Universal Declaration of Human Rights of the United Nations establishes the fundamental right to have access to decent and low-cost housing, indicating it as a key element for the health and well-being of people and the proper functioning of economies. To provide adequate and healthier living spaces to IDPs, it is then of paramount importance to accurately investigate the indoor thermal environment of these construction systems, also considering their possible improvement.

Passive climatization techniques are usually intended for the improvement of thermal performance improvement of traditional buildings. Despite rarely adopted in emergency architectures, they could be also effectively used to improve the thermal performance of lightweight temporary buildings, especially to reduce their indoor overheating in warm climates. Among passive cooling strategies, external finishing systems based on cooling materials, and in particular external coatings with nanotechnological and microtechnological additives, have several advantages, since able to reduce overheating without requiring high investment costs and/or involvement of specialized workers for their application. However, still few studies investigated the impact of this passive solution on lightweight emergency construction systems [11,12].

For this reason, in this work, the thermal performance of an innovative lightweight construction technology, called HOMEDONE, recently adopted in emergency scenarios (as a temporary housing solution and field hospital after the recent Central Italy earthquake (2016) and during the recent COVID-19 pandemic [13–15]), is numerically investigated before and after the application of cooling finishing materials. The system, based on the assembly of prefabricated high-density EPS panels internally reinforced with a tridimensional steel grid, has shown relevant indoor overheating when placed in hot climates, highlighting the need for implementing passive cooling strategies to improve its thermal performance in these contexts [14].

To increase the reliability of the numerical simulations, a numerical model of an experimental mock-up was firstly created and calibrated on measured data (indoor air temperatures). Then, the energy performance of a typical building is numerically investigated by taking into consideration different climatic zones. Finally, the variation in terms of cooling energy needs due to the use of cooling materials is assessed in different scenarios. This work is part of a wide experimental and numerical campaign aimed at investigating and improving the durability, thermo-hygrometric comfort, and energy performance of the proposed construction technology.

2. Materials and methods

This study can be subdivided into three main phases. In the first phase, a building energy model of an experimental mock-up is created and calibrated on experimental indoor temperature data gathered during a previous experimental campaign to provide reliable input parameters for the modeling and then to increase the reliability of the numerical simulations [14]. In the second phase, the energy demand for heating and cooling of a temporary/affordable housing solution is numerically evaluated considering different climatic locations. Finally, the effect on the energy demand of cooling finishing materials in different climates is numerically evaluated.

2.1. The HOMEDONE technology

The investigated construction system is based on the assembly of prefabricated high-density EPS structural panels (from 15 to 45 kg/m^3), internally reinforced by a three-dimensional electro-welded mesh made of galvanized steel (S235JR, the diameter of 3 mm) [14,15] (Figure 1). The system combines the concepts of modularity, transportability, self-construction, reuse, and recyclability to adapt to the different needs that may arise in an emergency scenario.

The composite panels can be provided with different lengths (generally 1.2m), widths (from 10 to 16 cm), and heights (from 2.4 to 3.4 m), allowing great adaptability to different uses. The limited size and weight of the panels allow easy transportation of the panels without the help of cranes. Then, the panels can be manually assembled by using a simple Allen wrench thanks to a patented steel hooking system. As a result, units can be provided both as readymade units, i.e. totally made off-site, or as kit supplies, i.e. totally assembled on-site to optimize and reduce transportation costs [4]. This allows realizing building even where work-site vehicles do not have easy access and specialized workers are not present, as may occur during emergencies or in developing countries.

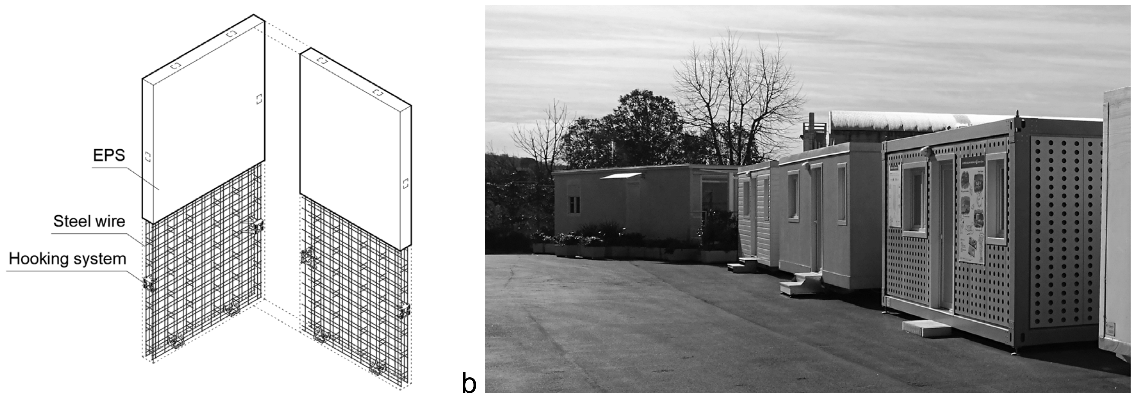

Figure 1. a) Reinforced-EPS panels and assembly; b) Prefabricated units with different dimensions and external finishing systems.

Air and water tightness are ensured by applying silicone glue in the joints between the panels, which provide sufficient sealing as evidenced by a previous experimental campaign [14]. A bituminous covering can also be applied to improve the waterproofing of the roof.

The surfaces of the panel are designed to allow external and internal coating with different types of materials (Figure 2). According to the requests, the external finishing layers can be made of plastic elements, steel sheets, or multi-layer cement-based systems (like those used in ETICS). Several tests were performed to verify the compliance of the panel and finishing systems with the technical regulations. In [15], for example, mechanical and durability tests were carried out aimed at verifying the safety in the use of panels covered by an external multilayer cementitious finishing system. As regards the internal finishing layers, those characterized by good moisture buffering capacity are recommended to avoid internal moisture-related issues, as highlighted in [14].

The foundations are made of a set of beams equipped with adjustable steel rods capable of ensuring the horizontality of the module on almost any surface, allowing to reduce the polluting impact on the site where the unit is located and to easily restore the pre-disaster conditions. Alternatively, it is possible to place the module on a cement plate.

Finally, the modularity of the system allows high adaptability to any spatial request, as well as progressive changes, expansions, redevelopments, reuse, and relocation from temporary sites to permanent sites. In this way, when no longer needed, the modules can be dismantled, sold, reused for other purposes, or included in permanent constructions.

2.2. Model establishment and calibration

To increase the reliability of the numerical evaluations, the indoor air temperature of a purposely built experimental mock-up, exposed to the hot-summer Mediterranean climate of Ancona (Italy), has been monitored (the experimental monitoring setup along with measurements accuracy is detailed in [14]). Then, a numerical energy model of the mock-up was created and calibrated on the measured sub-hourly indoor air temperature data. The mock-up, whose main façade is shown in Figure 2, has dimensions of 6.00 m × 2.40 m × 2.64 m and represents the smallest available unit that can be used in an emergency scenario. The thermal conductivity of the EPS panels is equal to 0.0288 W/mK, as experimentally observed in [14], while the U-values of the door and the window, both placed in the south façade, are equal to 1.420 W/m^2K and 1.305 W/m^2K, with a Solar Heat Gain Coefficient of the window equal to 0.4, according to the technical sheets. Other thermo-physical properties of the components are detailed in [14]. To focus the calibration process on the characteristics of the panels only, no finishing materials and no internal thermal gains were applied to the experimental unit. Thence, the thermophysical properties of the panels are the main input values to be tuned in the calibration process.

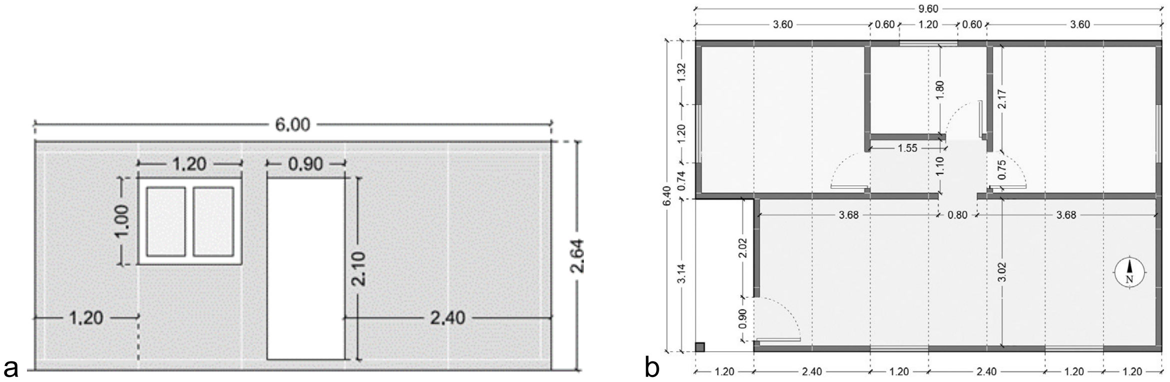

Figure 2. a) South façade of the experimental mock-up (dimensions in meters); b) the floor of the reference building adopted for the energy needs evaluation (dimensions in meters).

The software DesignBuilder ver. 6.1 [16] was used to model the experimental unit, while the building energy performance tool EnergyPlus ver. 9.4 [17] was adopted for the numerical simulations. A constant infiltration rate at 1 Pa equal to 0.143 h^{-1} has been assumed, according to the airtightness measurements [14]. Concerning the heat balance algorithm, a conduction transfer function combined with an effective moisture penetration depth (EMPD) was adopted as a heat balance algorithm, while an adaptive convection algorithm was considered for computing both internal and external convective heat transfer coefficients [17]. The moisture properties of the materials, needed to define the EMPD building energy model, were directly extracted from the DesignBuilder software dataset [16]. All the simulations were carried out by adopting 6 time-steps per hour. To ascertain the model accuracy, the Coefficient of Variation of the Root Mean Square Error (CVRMSE) and the Normalized Mean Bias Error (NMBE) between numerical and measured sub-hourly indoor air temperatures have been computed. The ASHRAE guidelines recommend values of NMBE and CVRMSE lower than ±10 and 30%, respectively, for considering the model as well-calibrated in case calibration on hourly values [18].

2.3. Numerical modeling of a temporary housing solution and application of cooling materials

To evaluate the energy needs of the construction system in a real use condition and different climatic locations, a numerical model of a temporary housing solution recently adopted in emergency camps and proposed as affordable housing in developing countries was created. The geometrical characteristics of the building are reported in Figure 4. All external and internal walls, as well as roof and floor, are made of reinforced-EPS panels, whose hygrothermal characteristics were directly derived from the numerical calibration of the experimental unit. Windows and external doors have the same thermal properties as those adopted in the experimental unit and detailed in [14]. Internal doors, instead, are wooden, with a thickness of 35 mm and a U-value of 2.82 W/m^{2}K. The floor panels are directly in contact with a concrete slab, used as a foundation, and internally covered by an 80 mm thick lightweight concrete slab with thermal conductivity λ, specific heat capacity ς and density ρ equal to 0.38 W/mK, 1000 J/kgK, and 1200 kg/m^3, respectively. To investigate the impact of cooling finishing materials on energy needs, three different external finishing system configurations are considered in this study. In the base case, the roof is covered by a black bituminous membrane with low albedo (0.10), while the walls are finished through an external 4 mm-thick cementitious render with an albedo of 0.40 (λ=0.72 W/mK, ς=840 J/kgK, and ρ=1800 kg/m^3). In the second configuration ("Cool roof", CR), the possible application of a cooling finishing material over the bituminous covering is considered, by increasing the roof reflectivity from 0.10 to 0.85. Then, in the third configuration ("Cool roof and walls", CRW), the application of cooling materials over all the external surfaces is considered (albedo equal to 0.85). As regards the internal gain and infiltration/ventilation rate, according to [19], a constant power density of 6.15 W/m^2 and 0.6 air changes per hour have been adopted to simulate a standard use condition. As emergency conditions and the demand for affordable housing can occur in any climatic context, several climates have been considered in this study to cover the widest possible range of environmental conditions. The adopted locations are listed in Table 1. To ensure homogeneous results among climates, the temperature setpoints are assumed constant and equal to 18 °C for heating and 24 °C for cooling, while the simulation outputs are reported in terms of annual cooling and heating energy needs. It should be noted that a temperature setpoint of 18°C does not guarantee internal thermal comfort in any context, especially when no solar irradiance is present. For this reason, further studies will evaluate the impact on indoor thermal comfort of this cooling strategy.

Table 1. Climatic locations considered in the numerical simulations.

City	*Köppen Classification* [20]	*Lat.*	*Long.*	*GMT*	*Elev.*	*CDD*	*HDD*
Singapore	Af	N1°22'	E103°58'	8	16	6374	0
Brasilia	Aw	S15°52'	W47°55'	−3	1061	4117	22
New Delhi	BSh	N28°34'	E77°11'	6	216	5363	278
Mexico City	CWb	N19°25'	W99°4'	−6	2234	2503	547
Abu Dhabi	BWh	N24°25'	E54°39'	4	27	6254	24
Ancona	Cfa	N43°37'	E13°31'	1	12	1750	2062
Sao Paolo	Cfa	S23°32'	W46°38'	−3	802	3826	179
Quito	Cfc	S0°9'	W78°28'	−5	2812	1366	1554
Concepciòn	Csb	S36°46'	W73°3'	−4	16	1207	1843
Johannesburg	Cwb	S26°7'	E28°13'	2	1700	2216	1052
Chicago	Dfa	N41°46'	W87°45'	−6	186	1743	3430
Montreal	Dfb	N45°28'	W73°45'	−5	36	1185	4493

3. Results

3.1. Numerical calibration

The calibration results of the numerical models are shown in Figure 5 in terms of comparison between measured and simulated indoor air temperatures of the experimental mock-up in four representative days. The numerical results show a high correspondence with the measured data with CVRMSE and NMBE values equal to 7.00 and -5.66%, respectively, i.e. far below the threshold values defined in the ASHRAE 14 guidelines to consider the model as well-calibrated (equal to ±10 and 30% respectively) [18]. Concerning the main property of the calibrated model, a high consistency between the initial and calibrated input values has been obtained. Indeed, to allow the match between measured and simulated data, it was sufficient to vary the albedo of the panels only, initially set equal to 0.4 and then modified to 0.9, which is in line with the high reflectivity for white surfaces observed in the literature (higher bound) [21]. All the other parameters, such as thermal conductivity of the components and airtightness, have been maintained equal to those experimentally observed in [14] or to those detailed in technical sheets. Therefore, a good consistency between the modeling assumptions (for example the absence of thermal bridges between panels) and the real characteristics of the construction system is found. The adopted modeling strategy can be then considered as sufficiently reliable, allowing to model the construction system within an allowable error margin.

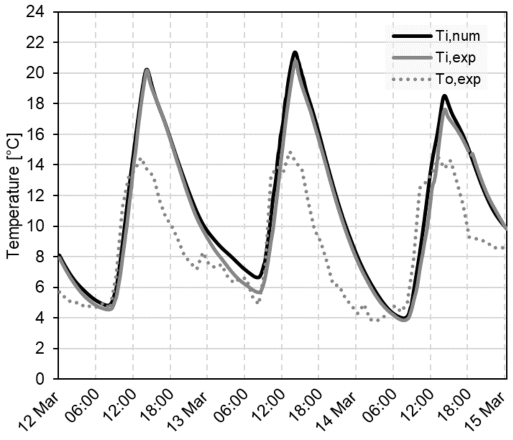

Figure 3. Comparisons between measured (exp) and simulated (num) indoor air temperatures (Ti) in three representative days. To: outdoor air temperatures.

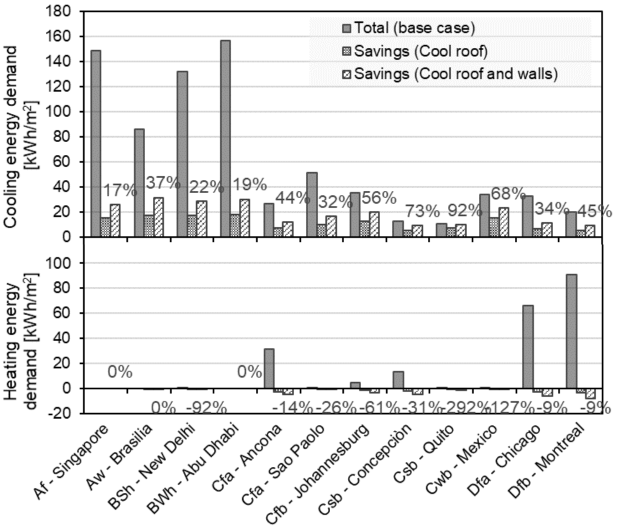

Figure 4. Energy demand for heating and cooling for the base case scenario and savings in the CR and CRW scenarios. Percentage values are referred to savings obtained in the CRW scenario.

3.2. Numerical simulation of a temporary housing solution

In Figure 4, the results of the numerical simulation of the reference building in terms of heating and cooling demand are reported for all the analyzed climates. The numerical simulations denote a high energy performance of the construction system in terms of heating energy demand (Q_H) due to the high level of insulation. This is particularly relevant if compared with other common emergency construction systems, such as container modules with insulating sandwich panels, generally characterized by lower thermal conductivity values and higher energy demand for space heating (more than double [22]).

Conversely, due to the indoor overheating in hot climates, the cooling energy demand (Q_C) of the system is particularly high in equatorial (A) and arid (B) climates, highlighting the need for improving the building energy performance in these contexts by adopting suitable passive cooling measures.

3.3. Energy demand reduction due to the application of cooling materials

Figure 4 shows the energy demand reduction obtained for both space cooling and heating after the application of cooling materials as external finishing for both the CR and CRW scenarios. The reduction of the albedo of the external surfaces allows reducing Q_C in all the climatic locations.

As expected, a higher reduction is obtained for the CRW scenario due to the higher number of external surfaces involved. In this case, however, a lower ratio between energy needs reductions and involved surface area is obtained if compared to the CR scenario, indicating cool roofs as more effective than cool walls in reducing indoor overheating.

In relative terms, for the CR scenario, the obtained Q_C reductions are between 10 and 20% for the equatorial climates (A), between 13 and 11% for arid climates (B), between 19 and 69% for temperate climates (C), and from 20 to 27% for continental climates (D). Similarly, the obtained Q_C reductions for the CRW scenario are between 17 and 37% for the equatorial climates (A), between 19 and 22% for arid climates (B), between 32 and 92% for temperate climates (C), and from 34 to 45% for continental climates (D). In absolute terms, however, these variations are higher in equatorial (A) and arid (B) climates, i.e. where the solar radiation is higher, with reductions ranging between 15 and 17 kWh/m^2 and between 17 and 18 kWh/m^2, respectively, for the CR scenario, and between 26 and 31 kWh/m^2 and between 28 and 30 kWh/m^2, respectively, for the CRW scenario. Lower savings are obtained for temperate and continental climates (C and D), according to the lower solar radiation, with absolute values ranging between 6 and 15 kWh/m^2 and between 5 and 6 kWh/m^2, respectively, for the CR scenario, and between 9 and 23 kWh/m^2 and between 9 and 11 kWh/m^2, respectively, for the CRW scenario. Analyzing the reductions in terms of heating energy needs (Q_H, see Figure 4), the increase of the albedo of the external surfaces always leads to an increase in energy needs if present, due to the lower solar energy absorbed by the opaque elements during the winter days. This decrease ranges between 1 and 3 kWh/m^2 for the CR scenario, and between 1 and 8 kWh/m^2 for the CRW scenario.

In any case, however, the increase in heating energy need is lower than the decrease of cooling one. This notwithstanding, it should be noted that in continental location (D) this difference is very low (as in the Montreal case), which could not justify the implementation of this strategy in this location or even lead to counterproductive results (Q_H increases higher than Q_C decreases).

For this reason, in these locations, it could be then more appropriate to recur to other types of passive cooling measures, such as seasonal passive cooling strategies.

4. Conclusion

The present study has reported some numerical results aimed at investigating and improving the thermal behavior of an innovative lightweight reinforced-EPS construction system developed for responding to the growing demand for emergency and low-cost building solutions. These activities are part of a broader experimental and numerical campaign aimed at defining and improving the performance of the system in terms of durability, thermo-hygrometric comfort, and energy efficiency.

The numerical results have shown that the investigated construction system can provide excellent results in terms of energy consumption in all the analyzed climatic contexts, especially for space heating. Due to the lack of internal thermal inertia that causes indoor overheating, indeed, high energy demand for space cooling is generally obtained especially in hot climates.

The numerical simulations have shown that a significant reduction in cooling energy demand can be achieved by applying cooling materials to the external surfaces in hot climates, i.e. where high indoor overheating may occur. This measure allows reducing the energy demand for space cooling up to 37% for equatorial and arid climates, and up to 90% for temperate climates.

Particular attention must be paid to the adoption of this strategy in temperate and cold climates, as in these contexts the obtained decrease in summer consumption can be counterbalanced by the increase of winter consumption, thus making the strategy completely ineffective or even counterproductive.

For this reason, future works will evaluate the possible application of seasonal passive cooling measures for reducing summer overheating in these locations.

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